

# Design recommendations for fibreglass reinforced tunnel softeyes

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**ABSTRACT:** This paper outlines the design challenges and recommendations for use of fibreglass reinforcement in tunnel headwall softeyes as learned through transit construction projects in the Greater Toronto Area (GTA). Tunnel boring machines were used to construct underground transit tunnels requiring the design of shafts with softeyes to facilitate tunneling operations. Variable ground conditions and shaft geometries lead to innovative headwall and tunnel softeye design applications using fibre reinforced polymer (FRP) elements (beams, reinforcing bars, and anchors). This paper outlines the challenges and benefits associated with designing and constructing shafts using various FRP systems including lessons learned throughout design and construction of over 20 structures through the past decade.

## 1 INTRODUCTION

The City of Toronto has been expanding its metropolitan transit network with a variety of new transit construction projects. A total of 31 new transit stations and 18.6 km (11.5 miles) of twin tunnel underground rail will be added in the Greater Toronto Area (GTA) public transit network with two recent projects: the Toronto York Spadina Subway Extension and the Eglinton Crosstown Light Rail Transit project. (TTC 2017, EllisDon 2016).

Due to existing infrastructure, ground conditions, and spatial constraints of existing surface infrastructure, these projects utilized tunnel boring machines (TBMs) to construct the underground tunnels requiring the design of various types of shafts and headwalls to facilitate underground tunneling operations. To allow for tunneling through the headwalls, these shafts were designed with “softeyes” - a section of the wall without metal reinforcement that allows the TBMs to tunnel through.

## 2 PURPOSE OF SOFTEYES IN TUNNELING

A softeye is a wall type which can be drilled through and penetrated by a TBM cutterhead. This can be accomplished in a variety of ways including: mass concrete non-reinforced drilled wall, Fibreglass Reinforced Polymer (FRP) secant pile or slurry wall, jet grout block, or ground freezing (Hunt & Finney 2008). In the GTA, we have used FRP secant pile headwalls in the following applications: Launch Shafts, Exit Shafts, Advance Headwalls, Mining Excavation Shafts, and other Access Shafts.

**Launch Shaft:** This type of shaft accommodates hoisting, assembly, launch of TBMs, and mucking operations (removal of tunneling spoils).

**Exit Shaft:** Designed to receive, disassemble, and hoist a TBM.

**Advance Headwalls:** Typically installed at boundaries of future excavations, such as underground subway stations, to allow the TBM to pass through the headwall prior to excavation of the future shaft.

**Mining Excavation shafts:** Access shafts to accommodate mining operations utilizing a Sequential Excavation Method (SEM) or New Austrian Tunneling Method (NATM). Access

Shafts are used to proactively provide access to the TBM for maintenance of cutter heads at some part through the tunnel drive between the Launch and Exit Shafts.

Each of these provides unique design challenges and requires design capacities, geometries, and other considerations for the uses of FRP reinforced secant pile headwalls

### 2.1 FRP in headwall designs

A fibre reinforced softeye can be accomplished in several ways. In all cases, the steel pile reinforcing typically used for the excavation support system is replaced in the softeye zone with FRP reinforcing. This reinforcing can consist of FRP beams bolted to similar depth steel beams or reinforced cages with fibreglass reinforcing bars through the softeye zone. In Toronto, FRP reinforced softeyes have been designed and used in a wide range of variable ground conditions and adjacent structure geometries, resulting design pressures with K values from 0.25 to 1.0, FRP excavated heights of up to 20 m (65 ft), and unsupported spans of up to 5 m (16 ft).

## 3 FRP DESIGN CONSIDERATIONS

Fibre reinforced polymer materials are considered suitable for use in softeyes mainly due to their ‘cuttability’ by the TBM’s cutterhead during tunneling operations. FRP exhibits brittle failure which is different from steel’s ductility. Brittle failure allows the FRP to break into pieces without obstructing the TBM during operation. Brittle failure is also a main consideration in the design of FRP systems, and one of the reasons why current design codes such as the CAN/CSA-S806-02 apply significantly more conservative factors of safety (FOS = 3 – 4) than other design materials (FOS = 1.5 – 2.0). Figure 1 illustrates the significantly different behavior of FRP and Steel anchor bolts.

The manufacturing process used to produce most fibreglass products, called pultrusion, results in an anisotropic material with directional material properties. Therefore, stresses in the transverse and longitudinal directions must be considered in design. This results in a significantly smaller allowable shear capacity compared to conventional steel beams. FRP also has a significantly lower modulus of elasticity than steel. This leads to specific design considerations when using a composite steel/FRP system like a Steel/FRP headwall. Table 1 outlines a

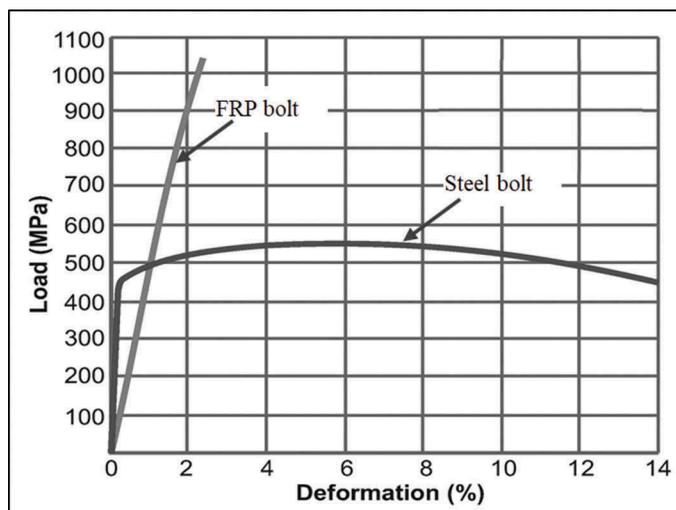


Figure 1. Comparison of material behavior of FRP and steel bolts (Mohanty et al. 2014).

Table 1. Mechanical property comparison of FRP beams vs. steel beams.

Parameter	Glass FRP shapes		G40.21 Structural steel $F_y = 350 \text{ MPa}$
	Lengthwise	Crosswise	
Ultimate tensile strength (MPa)	207	48.3	450
Ultimate compressive strength, (MPa)	20	110	450
Ultimate flexural strength, (MPa)	207	68.9	450
Modulus of elasticity – full section (MPa)	19300		200000
Shear modulus – full section, (MPa)	2930		77000
Ultimate shear strength (MPa)	31		231
Unit weight (kN/m <sup>3</sup> )	18		77

(Munn & Hudler 2018).

comparison in material property values between a typical FRP pultruded shape (I-beam) versus the typical steel pile secant wall reinforcing used in the GTA. The contrast in the modulus of elasticity of the two materials needs to be accommodated in the design and can lead to different deformation behavior of the two materials resulting in load redistributions in the system (Schürch & Jost 2006). For this reason, the steel/FRP connection is modelled as a hinge since moment transfer is hard to achieve due to strain compatibility issues. This poses a design challenge as the fibreglass beam has low shear capacity. Therefore, the concrete in the secant pile wall acts as additional reinforcing, and the strength should be increased to accommodate shear stresses that exceed the FRP reinforcing capacities. The authors have used concrete strengths ranging from 15 MPa (2200 psi) to 25 MPa (3600 psi) to act as additional shear reinforcing for FRP reinforced secant pile headwalls.

It is important to note the properties of FRP materials depend on the material used to reinforce the polymer (glass, aramid, carbon, etc.) and the manufacturing process used. As illustrated by the variability in the preceding examples, design strengths, design recommendations, and material property values from the specific manufacturers should be consulted when designing FRP systems.

### 3.1 Fibreglass beams

Secant Pile walls in the GTA are typically reinforced with steel I-Beams in low strength concrete (4 MPa/580 psi). This has led to FRP beams being more commonly used for softeye reinforcing, however FRP reinforced headwalls can have concrete strengths of up to 25 MPa (3600 psi). Excavators are used to trimming the rounds of the secant pile walls to accommodate bracing/support connections and the proposed permanent wall locations, where applicable. Due to the different geometries of the FRP sections and weaker material strength, damage to the FRP materials from the excavator has occurred, such as over-excavation through FRP pile sections and bolted splice connections being sheared off during excavation to the pile face as seen in Figure 2.

To achieve required capacities, FRP beams can also be built up using other FRP shapes to create composite design sections for loading cases where single FRP beams lack capacity. Figure 4 shows an example of a built up pile layout used for a FRP reinforced headwall for a TBM exit shaft. Special consideration needs to be given to bracing connection detailing (I.e. walers and corner bracing, etc.) and excavation activities when using built up FRP connections. In the project example shown in Figures 3- 4, the secant pile wall was not trimmed to the front of the steel pile flanges above the softeye to avoid damage to the built up FRP shape through the softeye.

Since FRP shapes come in a smaller variety of sizes and thicknesses than steel beams, special consideration for splicing beams and preferred pile layout in the headwall needs to be considered. Figure 5 shows examples of FRP/steel softeye splices using either FRP splice plates and bolts or typical steel plates and bolts.



Figure 2. Over-excavation through FRP pile flange (Left) and broken FRP bolts (Right).

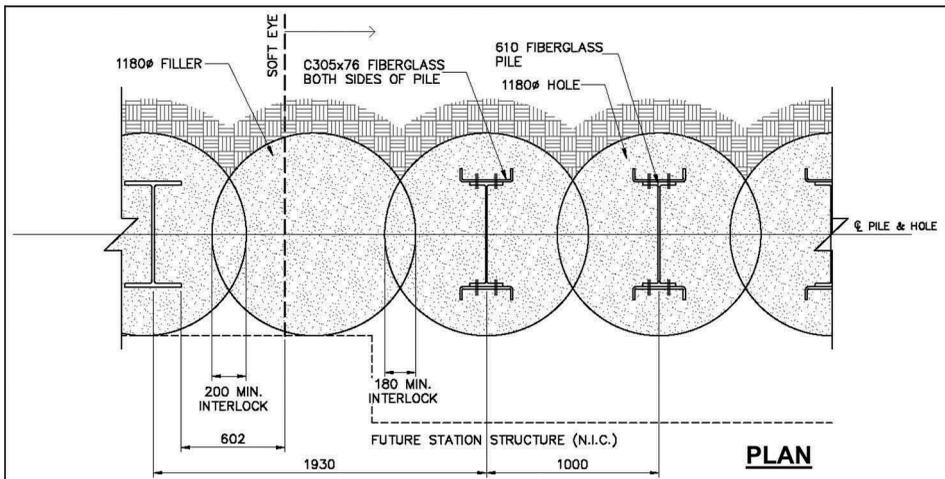


Figure 3. Example pile layout of built up FRP section (units in mm).

### 3.2 Fibreglass reinforced cages

Using reinforced cages with steel/fibreglass for headwall softeyes provides its own unique set of design challenges. Current fibreglass design codes specify conservative allowable stresses for fibreglass design (allowable = 30% ultimate) due to a number of factors (CSA 2009). These include the failure mode of the material, lack of differentiation between temporary and permanent uses, as well as the lack of historical data for use of FRP as a design material compared to other materials. This results in an increased number of bars in the FRP section of the cage to achieve the same required design capacity as the steel section. In the example



Figure 4. Breakthrough of TBM through FRP beam reinforced softeye.

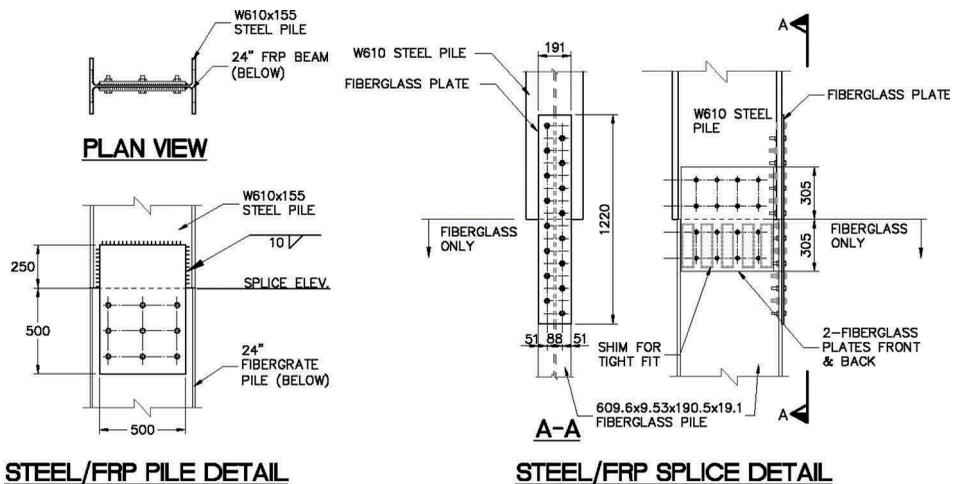


Figure 5. Steel/FRP splice details – Steel plates and bolts (left) and FRP plates and bolts (right).

illustrated in Figure 6, the initial design had an overall concrete cover of 100 mm (4 inch) but resulted in a small 50 mm (2 inch) cover between the inside of the drill casing and the outside of the cage during installation resulting in the fiberglass cage breaking in several holes during liner extraction. To resolve this issue, additional FRP ties were added to the cage, and an oscillator was used for liner extraction of the remaining piles to limit the torque applied to the cages from continuous rotation in one direction.

Design recommendations for design of FRP cages include:

- Increased cover between drill casing and cage reinforcing – 75 to 100 mm (3 to 4 inch);
- Special attention forces on cages during construction and concrete mix design;
- Use of reverse spiral shear reinforcing on the inside and outside of the cage in lieu of single tie shear reinforcing to limit shear forces applied to the cage during liner extraction; and
- Additional U-bolt reinforcing at splice connections where large forces are transferred;

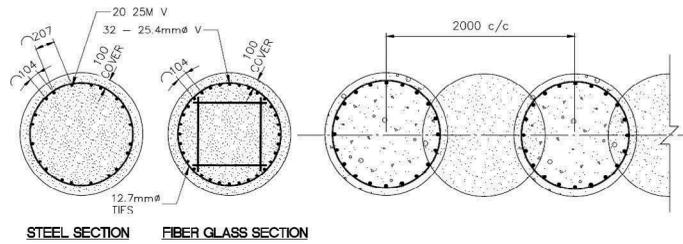


Figure 6. FRP/steel cage reinforcement detail (left) and pile layout example (right).

### 3.3 Fibreglass anchors

The other strategy used for design of Launch or SEM shaft headwalls is the addition of fibreglass anchors to decrease bending in the FRP pile section, and decrease the shear at the steel/fibreglass splice connections. These anchors are precluded for use in an Exit shaft due to the nature of the mining activities – the anchors would become damaged as the TBM approached the headwall prior to them becoming redundant resulting in a lack of support for the earth and TBM pressures.

Use of these anchors has resulted in simplified pile layouts due to the decrease in required fibreglass material, as well as a decrease in the required concrete strength to resist the shear at the connections. Figure 7 shows the design detail developed for use of the fibreglass anchors. Due to the limited availability of high tensile capacity fibreglass anchors, three 25 mm (1 inch) FRP bars were used per location to achieve the required design capacities. Due to limited availability of FRP anchor plates and other bolt accessories, the secant pile wall had to be further broken around to allow enough room to separate the FRP bars for three separate anchor connections at the face of the wall. These FRP anchor connections were recessed into the secant pile wall to allow the bars to be trimmed back. The recess was filled with concrete prior to launching the TBM to allow for a continuous mining face. The higher concrete strength of the secant pile wall was used to transfer the forces rather than traditionally welded anchored connections.

### 3.4 Sequential mining

Use of the FRP anchors has also allowed for larger design heights and different shaft geometries since internal bracing of the FRP beams is not required. This has allowed for more open

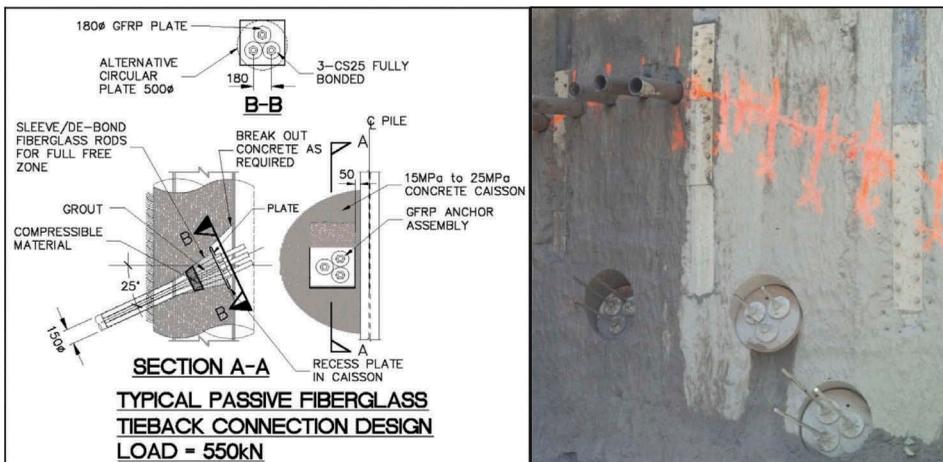


Figure 7. FRP anchor connection detail (left) and example of use at a launch shaft (right).



Figure 8. Mining access shaft headwall with FRP anchors – Sequential mining in progress.

excavations, and sequential mining of SEM headwalls as anchor elevations can be customized to the required geometry. Figure 8 shows a progress photo of the excavation for the SEM access shaft to allow mining for future light rail station using the Sequential Excavation Method. Particular attention needs to be directed at the breakthrough sequence of these headwalls as anchors need to be positioned so the excavation support is stable in all stages. Figure 9 below shows a schematic of the SEM breakthrough. Examples of issues encountered:

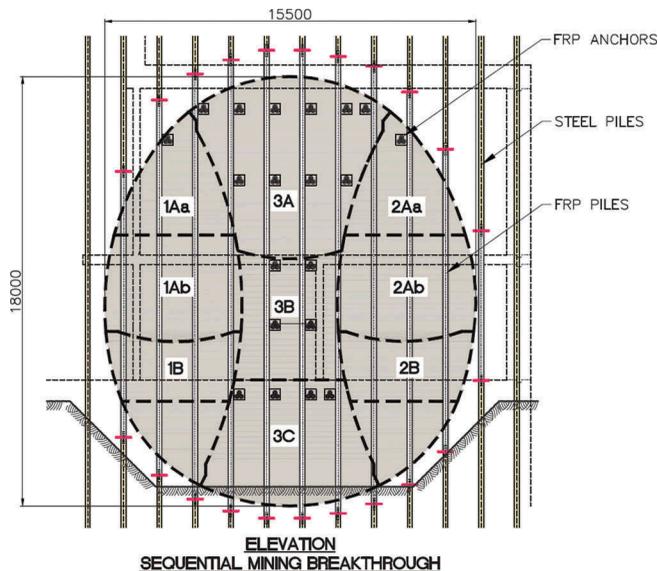


Figure 9. Mining access shaft elevation view – Mining breakthrough stages (Units in mm).

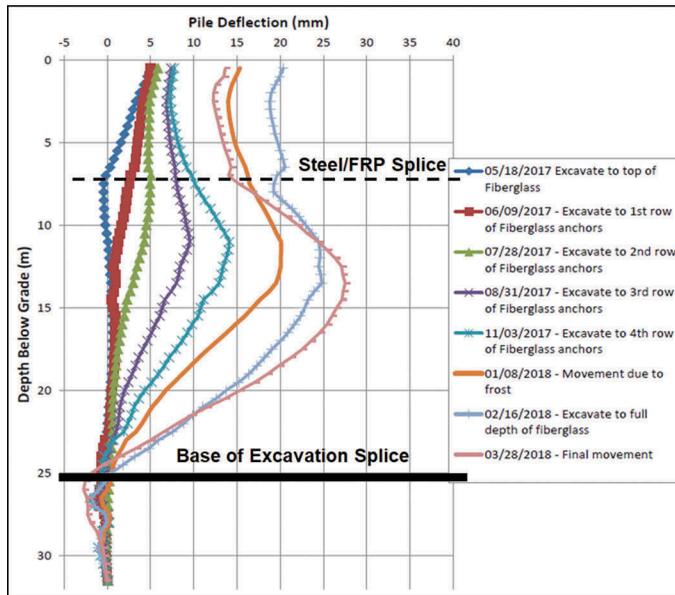


Figure 10. Steel/FRP pile inclinometer results.

- Cantilever lengths during intermediate stages need to be minimized due to fiberglass strength properties.
- Steel-FRP connection can only transfer shear load
- 3-dimensional geometry needs to be fully understood to avoid conflict between excavation support and the SEM tunnel.

The 18 m fiberglass span of the SEM opening was more than double the span for the headwalls previously designed and constructed, therefore a more comprehensive monitoring program was implemented to confirm the design. The performance of the steel and fiberglass pile was measured using an inclinometer attached to the pile along the full depth (Figure 10). While the movement over the FRP section appears high, it is only 5mm higher than the steel section above which is internally braced. This increased flexibility and resulting movement was expected due to the material properties and use of passive FRP anchors. In addition, the splice was assumed to behave as a pin which only transferred shear to the steel sections above and below the softeye. The overall softeye deflection supports this design assumption by the observed change in deflection pattern at the splice location.

#### 4 GENERAL CONSTRUCTABILITY CHALLENGES

Throughout the design and construction of these FRP reinforced systems, several constructability challenges have been experienced.

##### 4.1 *Hoisting/assembly*

Due to the low modulus of elasticity of the FRP reinforcement, the designer and contractor should work closely to understand the forces which may be encountered during hoisting and placement of the FRP reinforcement to ensure the cage or pile integrity. To minimize these forces, two different systems have been used in the GTA:

- Pre-drilled assembly holes – Vertical splicing over an additional drilled hole followed by vertical hoisting and placement of the reinforcement into the drilled secant pile wall. Also known as “Dummy” holes. (Figure 11).
- Support frames to act as a rigid spine to support the FRP reinforcement during the lifting process. Once the cage is vertical, the spine is disconnected prior to lowering the cage in the drilled hole (Figure 12).

#### 4.2 TBM forces

The Shoring wall designer must understand the temporary supernormal loading pressures, which may occur when the TBM is approaching the back of the shoring headwall prior to breakthrough. Earth Pressure Balance Machine’s used in the GTA can impose a pressure of up to 200 kPa (30 psi) on the back of the shoring headwall. To ensure adequate FRP Exit Shaft Headwall performance, removable internal bracing can remain in place until TBM makes contact with the back of the headwall and earth pressure forces are negated.

#### 4.3 Softeye placement accuracy

Placement of the FRP/steel reinforcing requires coordinating installation of the FRP within tolerances necessary for tunneling by the headwall Shoring Contractor. This can be particularly challenging when trying to mimic the circular tunnel liner shape with the FRP softeye.

#### 4.4 Monitoring programme

Based on the design challenges mentioned above, a quality monitoring programme for the temporary FRP walls in softeye applications is prudent. On these projects, a combination of 3D precision survey monitoring, inclinometers, and load cells on the anchors between the tunnels were successfully used.

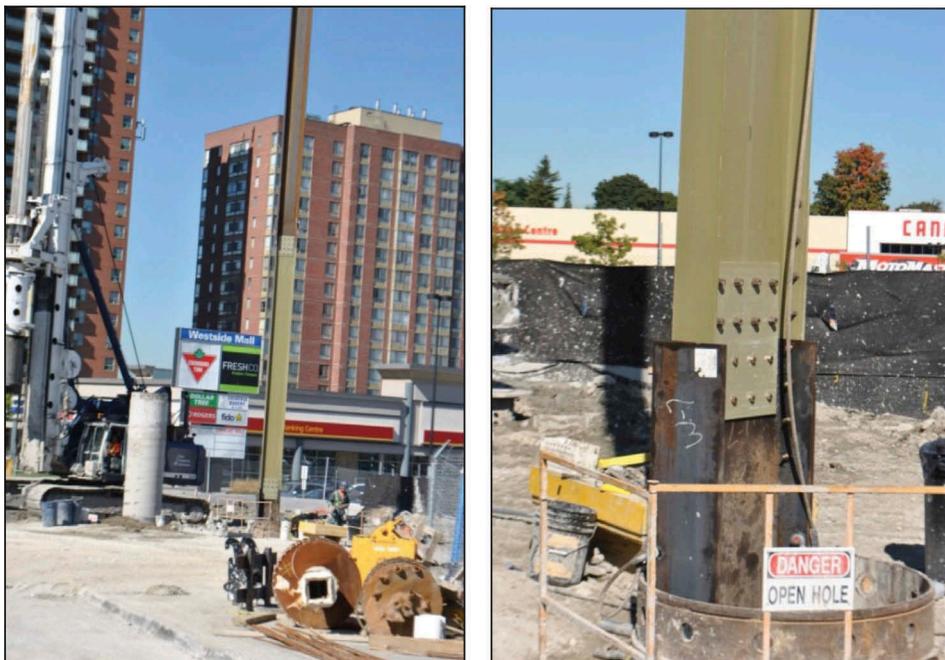


Figure 11. Fabrication and Installation of FRP/Steel Beam over Pre-drilled Assembly Hole.



Figure 12. Steel/FRP Cage Assembly on Spine Support Beam prior to Lifting.

## 5 CONCLUSIONS

Underground transit infrastructure projects in metropolitan areas provide an excellent opportunity for use of Tunnel Boring Machines (TBMs) to minimize impacts to existing surface and shallow infrastructure and surrounding communities. Use of TBMs requires construction of various Launch, Exit, and Auxiliary Shafts to facilitate tunneling operations requiring the design of shaft headwall softeyes. The use of FRP reinforcement and bracing has proven to be an effective and efficient means of providing structural support of the shaft and suitability for accommodating tunneling operations. The design of FRP systems provides unique construction challenges compared to more common construction materials; therefore, special attention needs to be given to material properties and constructability challenges. Overall, use of FRP has been found to be the most effective solution for softeyes in large diameter tunneling applications in various soil conditions in the Greater Toronto Area.

## REFERENCES

- Canadian Standards Association (CSA), 2009. CAN/CSA-S806-02. *Design and Construction of Building Components with Fibre-Reinforced Polymers. Rev. 5.* 177p.
- Canadian Institute of Steel Construction (CISC), 2010. *Handbook of Steel Construction, Tenth Edition.*
- EllisDon, 2016. *Toronto Eglinton Crosstown LRT*, viewed 16 April 2018, <http://www.ellisdon.com/project/eglington-crosstown-lrt/>.
- Hunt, S. W., Finney, A.J. 2008. Mitigating Tunnel Launch and Reception Challenges. *Society for Mining, Metallurgy & Exploration*, 812–823.
- Mohanty, S., Vandergrift, T., Ross, T., Hwi, G., Lee, M. 2014. Fiber Reinforced Polymer Rockbolts for Ground Control in a Strong Jointed Rock Mass. *33rd International Conference on Ground Control in Mining*, 193–198
- Munn, S., Hudler, H. 2018. Tunnel Headwall Softeyes: Fiberglass Design Applications and Constructability Challenges. *43rd Annual Conference on Deep Foundations*, 302–311.

- Schürch, M., Jost, P. 2006. GFRP Soft-Eye for TBM Breakthrough: Possibilities with a Modern Construction Material. *International Symposium on Underground Excavation and Tunnelling*. 397–404.
- Strongwell, 2016. *Strongwell FRP Specifications Section 06600 Fiberglass Reinforced Polymer (FRP) Products and Fabrications*, viewed 17 December 2018, <https://www.strongwell.com/wp-content/uploads/2015/08/StrongwellSpecs-FRP-Structural-Shapes-and-Plate.pdf>.
- TTC, 2017. *Toronto-York Spadina Subway Extension - Overview*, viewed 16 April 2018, [https://www.ttc.ca/Spadina/About\\_the\\_Project/Overview.jsp](https://www.ttc.ca/Spadina/About_the_Project/Overview.jsp).